Technical Report

Plans for Muography of Samail Ophiolite

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Abstract

Oceanic lithosphere cycling produces critical resources for the economy and governs the occurrence of various natural hazards from earthquakes to volcanic eruptions. Only a small portion of the shallow oceanic lithosphere is explored. The physical nature and geological meaning of the upper and lower crust boundaries and Mohorovičić discontinuity (Moho) between the oceanic crust and mantle are poorly understood. Direct observations of oceanic crust were conducted in two oceanic drilling holes; however, the Moho has not yet been reached. Former Moho transition zones are exposed on land in numerous ophiolites around the world; thus, the ophiolites are a very important clue to understand the correlation between ocean crust-mantle structure and geology. The Samail Ophiolite is the most promising analogue for oceanic lithosphere. We plan to conduct muography of the Samail Ophiolite to understand the density stratification of the oceanic crust to the mantle, which regulates the geological structure of the oceanic crust to mantle. We discuss the scientific background, the simulation studies, and the design of the muographic surveys.

Keywords: cosmic-ray muons, muography, oceanic lithosphere, moho, ophiolite
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1. INTRODUCTION

Oceanic lithosphere is built up from the crust and the solid uppermost layer of the mantle and covers about 60% of Earth's surface [1]. The oceanic crust is formed by decompression melting of the upper mantle, where mid-ocean ridges spread apart; it is ageing as it moves away from the mid-ocean ridges and destructs at subduction zones [2, 3]. This evolution generates a large-scale matter and energy cycling that produces natural resources and generates natural hazards.

A layered structure has been revealed for the lithosphere by seismic measurements. These are the sediments (Layer 1), upper crust (Layer 2), lower crust (Layer 3), and upper mantle (Layer 4). Two transition zones have been found between the upper and lower crusts and between the lower crust and upper mantle where fundamental changes in rock composition occur. The deeper seismic boundary is the so-called Mohorovičić discontinuity zone, shortly Moho. The Moho lies at a typical depth of 30 km and 6 km beneath the continental crust and oceanic crust, respectively.

Combining the geophysical surveying of ocean basins and petrological studies via in situ sampling of the segments of oceanic lithosphere in different tectonic environments is expected to advance the understanding of the nature of oceanic lithosphere. Ocean drilling has been proposed more than seven decades ago to uncover fundamental knowledge about Earth's subsurface processes. The sampling of oceanic lithosphere has already revealed critical pieces of evidence about plate tectonics, break up of continents, etc. To date, a small portion of the shallow oceanic lithosphere has been explored (Figure 1): 38 boreholes reached the depth of 100 m beneath the ocean floor [4], and only two drilling holes, namely, 504B (sub-basement depth of 1841 m) and 1256D (subbasement depth of 1293 m), reached the sheeted dikes through the uppermost basaltic lavas. Recently, Integrated Ocean Discovery Program's (IODP) MoHole to Mantle (M2M) drilling proposal aims to reach the Moho and the underlying mantle at three candidate sites including the Hawaiian arch and on the Cocos Plate (e.g., see [5]). The drilling vessel Chikyu was specifically designed for this project; however, MoHole drilling has not yet been conducted due to various technical challenges that require engineering solutions. The lack of samples from these transition zones results in the fact that the physical nature and geological meaning of the upper and lower crust boundaries and Moho remain poorly understood to date.

The so-called Penrose model proposed that ophiolites are ancient intact segments of oceanic lithosphere created at fast-spreading mid-ocean ridges and preserved on the lands [6]. The ophiolites comprise the following segments from top to bottom

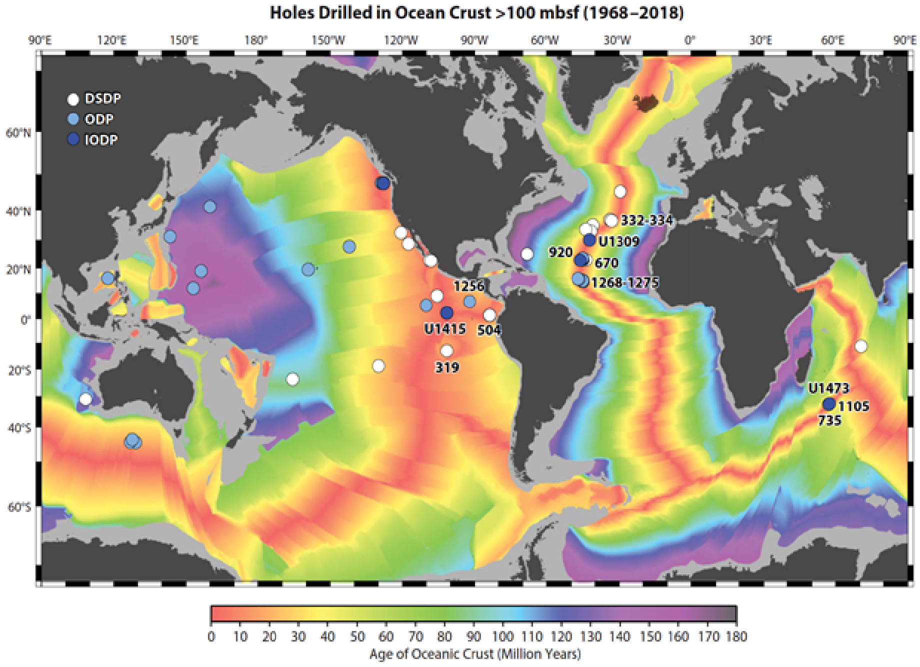

FIGURE 1: The locations of oceanic drilling holes with depths greater than 100 m below sea floor (mbsf) are shown by the filled circles [4]. The colors show the age of the oceanic crust (see [4] and references therein).

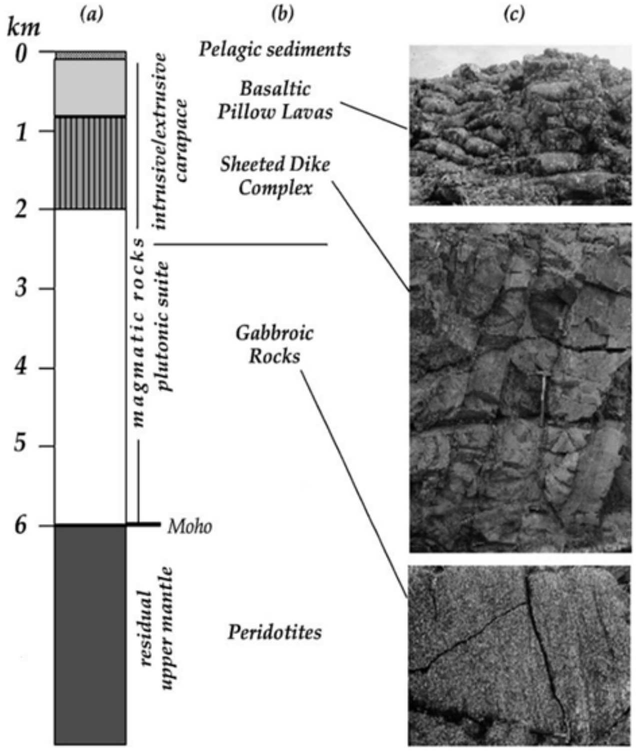

FIGURE 2: Segments of the Samail ophiolites in Oman are shown. (a) A schematic drawing about the thicknesses of different segments, (b) a list of stratigraphic layers, and (c) corresponding photographs are shown [9]. We note that the upper, middle, and lower photographs cover different surfaces of a few ten square metres, a few square metres, and a few square decimetres, respectively.

(Figure 2): sediments, basaltic extrusive rocks, sheeted dike complex, gabbroic rocks, and ultramafic rocks. Christensen and Smewing [7] found that the seismic properties and thickness of the segments in the Samail Ophiolite in Oman show similarities with the Pacific crust and upper mantle formed on intermediate- and fast-spreading ridges. The ophiolite preserves the world's largest complete oceanic crust-mantle sequence up to 14 km thick, extending 500 km long and 100 km wide. The Samail Ophiolite is considered to be one of the most complete analogues for the oceanic lithosphere [8]. Combining the geological studies of this ophiolite and the seismic surveys of the structure of the Pacific plate can provide access to the deep crust and the Moho transition zones and can give an important clue to advance our knowledge about the correlation between oceanic structure and Earth's geology.

Recent seismic surveys have shown that the Moho structure varies from sharp single reflections, multiple reflections, blurred diffused reflections, and no reflections [10]. In the Samail Ophiolite, the lithological boundary of the "Moho" is a transition zone where mantle harzburgite gradually changes into the lower crustal gabbro [11, 12]. In the paleoridge segment centre, rising magma reacts with the mantle harzburgite to develop a thick Moho transition zone of alternating dunite and gabbro layers. This may form the Moho with multiple reflections. In the magma-depleted segment ends, on the other hand, a thin, flat Moho transition zone is formed due to limited magmatic reactions. This may exhibit a sharp single reflection. Because of the high magma supply at the segment centre, the entire crust extends solely by magmatic intrusions, resulting in a steep bulk density gradient between the upper gabbro, frozen axial melt lens, and the foliated gabbro, cumulus minerals beneath the melt lens. This may explain the existence of Layer 2-3 (upper and lower crust) boundary below the gabbro that encountered at the bottom of Hole 1256D [13, 14]. In the magma-deficient segment ends, the crust extends by fault and magmatic intrusion in the upper and lower parts of the crust, respectively. The resulting differences in fracture density and porosity may control the Layer 2-3 boundary like in Hole 504B [15]. Therefore, examining the intrasegmental variability of the geological structure of the Semail Ophiolite provides a clue to understanding the enigmatic variability of the oceanic Moho and the factors that determine the Layer 2-3 boundary.

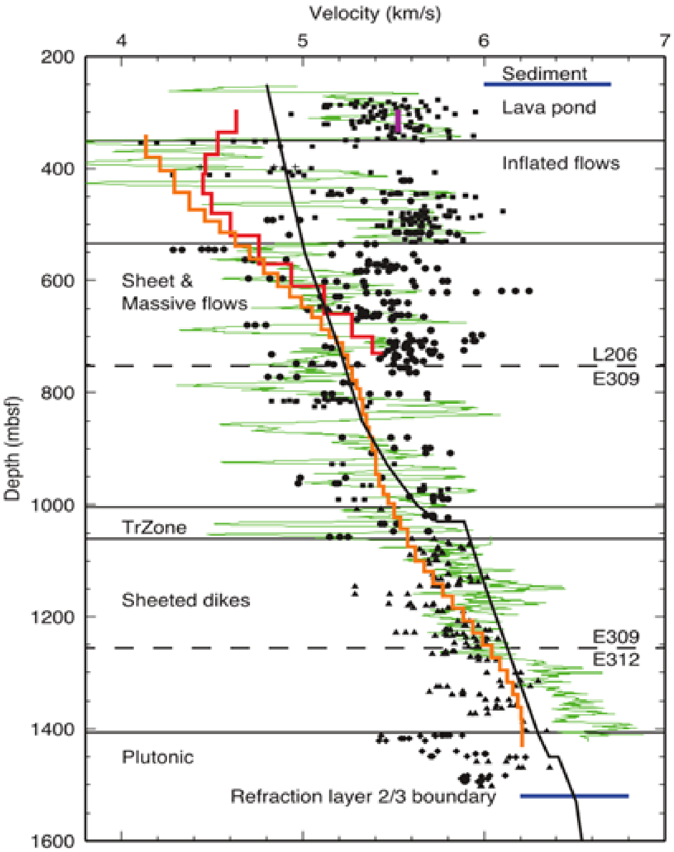

FIGURE 3: A compilation of velocity versus depth data quantified by laboratory measurements of minicubes (black dots), sonic logs (green-colored lines), and inversion of seismic travel times (red-colored and orange-colored lines) by Swift et al. [14].

Although applying different techniques to research the nature of oceanic lithosphere is an effective approach, there are discrepancies between the different measurement techniques that bias the interpretation. Figure 3 shows an example of the inconsistency between the different techniques applied for reconstructing the seismic velocity versus depth below the sea floor profiles [14]. Acoustic wave velocity measurements of core samples extracted from drilling Hole 1256D (black dots) significantly differs from the sonic logs (green-coloured lines) and from the P-wave velocities measured by ocean bottom seismometers (red-coloured and orange-coloured lines). Similarly, there is a discrepancy between the sample-based and logging-based seismic data from the ophiolite. These inconsistencies originate from the disparity between the specimens (typically only up to a few tens of centimetres in diameter) and the resolution afforded by the seismic technique (on the order of kilometres). In addition, lithological changes occur both horizontally and vertically ranging from a few centimetres to several tens of metres. Therefore, the sample-based seismic velocity structure is biased by the scarce sampling density. Reconstructing the high-resolution mass density structure of crustal and Moho transition zones in the Samail Ophiolite is expected to significantly advance our knowledge about the geologic nature of the upper/lower crustal and crustal/mantle transition zones.

We focus on developing and implementing the novel remote and passive geophysical method and visualisation technique called muography and exploit its spatial and density resolving capabilities [16, 17, 18, 19]. Figure 4(a) shows a schematic drawing of muographic surveying for exploring the Moho that lies between the crust and mantle layers of an ophiolite nappe. We plan to conduct high-definition muographic surveying of the density structure through the Moho transition zones located to the north of Wadi Jizi and at wadis Fizh and Hilti at the centre, northern and southern end of the paleoridge segment of Samail Ophiolite, respectively. We also conduct muographic observations through the upper and lower crust boundaries along the above wadis. By integrating the muographic and geological data, we will elucidate the relationships between the geological structure and the density structure of the oceanic crust-mantle and how and why they vary along the paleoridge segment. Figure 4(b) shows the map of the northern Samail Ophiolite, in which the red stars denote the measurement site candidates. We aim to conduct the joint analysis of muographic data with the log data acquired from ophiolites and seismic data of the Pacific Plate (that is the target of the IODP M2M proposal) to infer the local structure, lithology, and possible creation processes of Moho at fast-spreading mid-ocean ridges.

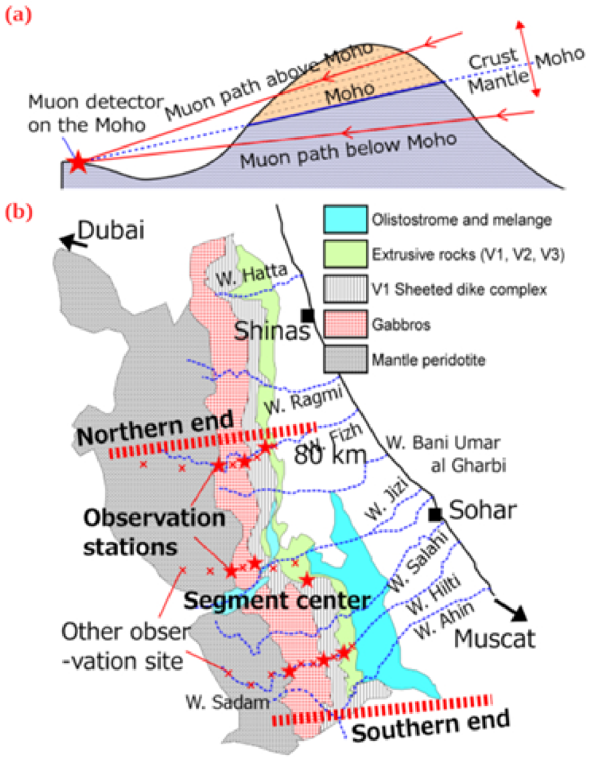

FIGURE 4: (a) A schematic drawing of muography of the Moho transition zone through ophiolites. The muon detector (red star) is oriented to the plan of the Moho. (b) The map of the Samail ophiolites with the main stratigraphic layers. Red stars denote the locations of measurement site candidates. Red crosses shows the locations of possible measurement sites. Red dashed lines, respectively, show the northern end and the southern end of the ophiolites. The black solid line shows the end of the land above the level of the Gulf of Oman. The "W." denotes Wadi in the names of locations.

2. INSTRUMENTATION

Multiwire proportional chamber (MWPC) muography observation systems (MMOS) will be applied for the muography of the ophiolite [20, 21, 22, 23]. Figure 5(a) shows a photograph of an MMOS with seven MWPCs and five two-centimetre-thick lead plates with stainless steel coverage. The lead plates are installed in the MMOS for absorbing and deflecting the low-energy (typically sub-GeV) muons that are observed from the directions of the studied structure but did not penetrate it (Figure 5(b)) [19].

The combination of MWPC technology with custom-designed electronics, microcomputers, and corresponding software frameworks allowed for the development of compact, remotely controllable tracking systems that could operate reliably with high detection efficiency (>98%) in harsh and varying environments, such as during typhoon season at Sakurajima volcano, Kyushu, Japan (see [22] and references therein), or in karstic cave systems and underground mine tunnels with high humidity (see [23] and references therein). The power consumption of a tracking system including all detector elements is approx. 5 W. These instruments can

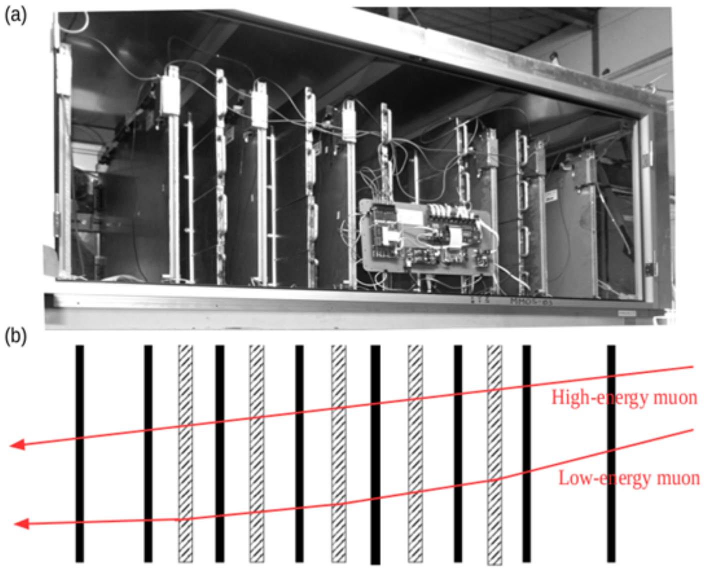

FIGURE 5: (a) A photograph about a Multiwire Proportional Chambers-based Muography Observation System (MMOS) in the Sakurajima Muography Observatory. (b) A schematic drawing of MMOS in which the red arrows represent the trajectory of muons. Black rectangles show the tracking layers and hatched rectangles show the lead shielding plates applied for absorbing and deflecting the low-energy particles which do not penetrate the structure to be imaged but observed from its directions.

be supplied by two 100 Ah batteries for more than two weeks on remote sites (e.g., see [24, 25, 26]). These instruments have already been applied successfully for muography of Earth's subsurface [24, 25] and human-made infrastructures [26, 27].

The detector maintenance works will be conducted by local collaborators. The replacement of batteries and data downloading are planned to be conducted every 2-3 weeks. The gas supply will be sufficient for 3-4 months.

The main challenges on the field are expected to be the relatively high temperature and large daily temperature variations. The actual MWPCs operate reliably below the temperature of 45°C which limits the data collection period from September to April. The variation in gas volume correlates with the variation in air temperature. When temperature decreases, the volume decreases by a few litres, which results in air inflow which decreases gas gain and thus the efficiency of muon detection. The application of gas buffer volumes, such as large tubes, after the last detector in the gas system is expected to compensate this effect as it was demonstrated by Nyitrai et al. [23].

3. MODELLING OF MUOGRAPHIC OBSERVATION

The optimization of experimental arrangement and estimation of data acquisition time are performed via modelling the muographic measurement. Here, we present an example for the Moho at Thuqbah. Figure 6(a) shows a photograph about the crust consisting of layered gabbros, the Moho Transition Zone (MTZ), and the harzburgite mantle. Figure 6(b) shows the time of data acquisition required to differentiate the crust (density of $3.13\,\mathrm{g/cm^3}$) from the mantle (density of $3.36\,\mathrm{g/cm^3}$) on a proper confidence level through this mountain ridge by muographic measurement conducted in the UTM zone 40R at Northing of 2683930 m, Easting of 429131 m, and altitude of 765 m. Here, the muographic observation system consists of MWPCs with a size of 120 cm by 80 cm within a length of 100 cm and oriented to an azimuth angle of 70° from north and 5° from the horizontal direction. The muon fluxes are calculated by integrating the muon spectra [28]. The time of muographic imaging is expected to be 180–360 days at each measurement site due to the excessive rock thickness, except at the north of Wadi Jizi, where the data acquisition is expected to be below 30 days across the moderated thickness of below 100 m.

4. SUMMARY

The geological nature of the crustal and crust-mantle (Moho) transition zones is still poorly understood to date. The Moho has not yet been reached by ocean drilling. The Samail Ophiolite provides a window into the oceanic lithosphere. Muography is a novel technique that allows the remote and passive exploration of the internal structure of solid, liquid, and gas media with a relatively good (a few metres for large-sized edifices, such as volcanoes or ophiolites) spatial resolution by measuring the flux of cosmic-ray muons which penetrated the studied media. The application of muography for density imaging of the ophiolite can overcome the sampling limitation of conventional geophysical techniques. Joint analyses of muographic and petrological data collected in the Samail Ophiolite and seismic data of oceanic lithosphere are planned to be conducted for (1) exploring the lithological constituents

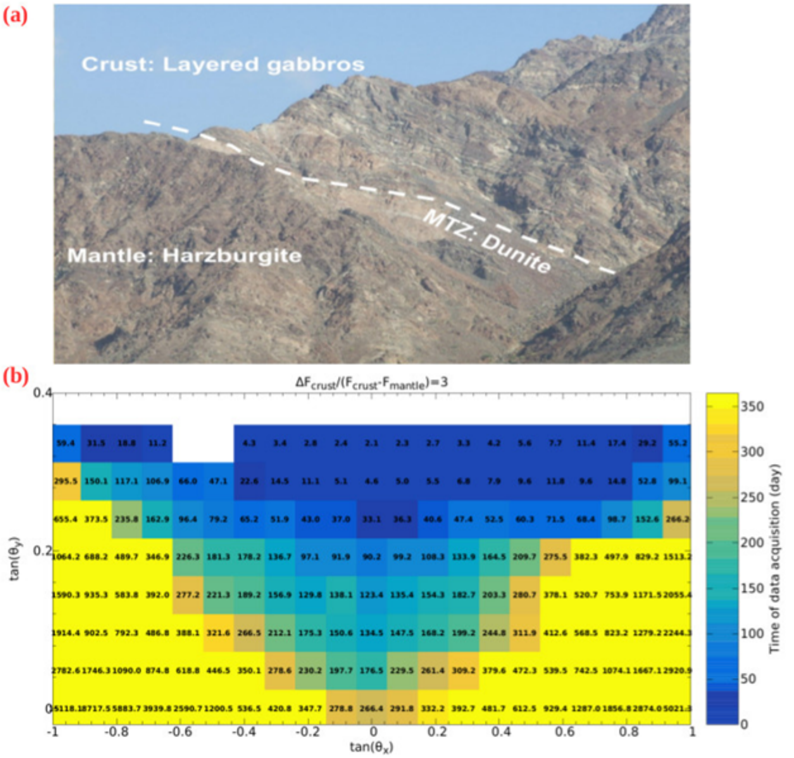

FIGURE 6: (a) A photograph of the Moho Transition Zone (MTZ) to the north of Wadi Jizi. (b) Time of data acquisition required to distinguish the crust from the mantle with 3 standard deviations is shown as a function of horizontal and vertical directions in the natural coordinate system of the muographic observation system.

and mantle processes that form the Moho and (2) studying why and how the structure of oceanic crust changes within a segment of the fast-spreading ridges.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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